Biomorphic Explorers

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Solar System exploration could be substantially enhanced if it were possible to deploy a large number of small, inexpensive, independent, autonomous platforms, each with its own dedicated microsensors, power unit, and communication system into the environment of planetary bodies. The Sojourner rover's success on the surface of Mars has proven beyond doubt that a mobile platform on a planetary surface, equipped with sensors, can provide new science data. The concept of multiple mobile explorers is expected to greatly enhance the science return.

Small, mechanical platforms which mimic the mobility of biological systems, could be built at low cost, instrumented and used as platforms for carrying scientific instruments. We call these systems *"Biomorphic Explorers"*. These would be particularly useful for exploration of sites difficult to reach by traditional platforms. Bio-morphic explorers would complement the abilities of the larger and relatively expensive exploration platforms (e.g. landers, rovers, and aerobots). They may possess *varied mobility modes*: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. Preprogrammed for a specific function, they could serve as information beacons, spread over the exploration site, autonomously looking for/at the object of interest. *Co-ordinated/co-operative exploration scenarios* are conceivable, for example, in a hierarchical organization, these bio-morphic explorers would report to the next level of exploration mode (say, a large conventional rover) in the vicinity. This would allow a wide-spread and affordable exploration with a substantial amount of scouting for information about new, currently non-accessible areas at lower cost and risk, combining a fast running rover to cover long distances and deploying numerous biomorphic explorers for in-situ sensing and local sample analysis/acquisition.

Realization of the vision of small expendable bio-morphic explorers requires at least four key components: (1) microsensors, (2) micropower, (3) advanced mobility and (4) microcommunication devices. The development of three out of these four essential components (except the advanced mobility) is already driven by multibillion dollar commercial market forces. For example microsensors such as microimagers are already being miniaturized to serve the voracious appetite of digital imaging business for surveillance, security, science, and entertainment. Solid state high-power-density batteries are advancing at a rapid pace, driven by the development in cellular phones, handheld computers, long life watches, and other electronic gadgets. Low-power, limited range, low-bandwidth communication, adequate for the explorers, has also been addressed aggressively in recent years, to target the mass market of product ID tags and inventory control. However, the only component that has not received equivalent attention from the commercial market forces is advanced mobility and control. Biomorphic Explorers leverage from innovations in primarily two areas: (1) bio-mechatronic designs inspired by biological mobility and (2) biomorphic controls emulating neuro-reflexive sensory motor control architectures.

With reference to mobility, a few different scenarios of interest will be described with visualization of how biomorphic explorers will be particularly suited. The first scenario described is of a worm like explorer that can crawl under rocks, crawl into cracks in rocks or even burrow under loose soil. These biomorphic worm explorers would be for example deployed from a lander/large rover. The explorers with imaging sensors would be spread in the exploration site to first look for fresh cracks for example based on their fractal content of the crack and color of the rock. If a fresh crack is found, the explorers go deeper into it looking for relevant samples. This could be organized by co-operative functioning of the different species of the explorers, for example the imaging explorer would conduct the initial survey and the sensing explorer would then probe further to look say specifically for water in the areas of interest. Another scenario described is for imaging the stratigraphy of the rocks/deposits on the canyon walls and the sedimentary layering at the bottom of the deep canyons such as Valles Marineris on Mars. A hopping explorer would go up from level to level imaging the sedimentary layers from bottom up. On the other hand, propulsive disc explorers or gliders dispersed/deployed by an orbiter or aerial mother craft would maneuver down slowly in a controlled manner, collecting data on their way from the top down. Disc explorers would utilize propellants that could be renewably produced by in-situ resource utilization on Mars. These would be ideal for atmospheric and meteorological studies as well. Gliders of different kind are uniquely suited for exploring the canyon walls more closely for possible volcanic deposits. A fourth scenario is of exploring subsurface oceans underneath deep layers of ice such as in Lake VOSTOK terrestrially and on Europa.

Current wheeled mobility mechanisms are generally designed for, and therefore limited to, only pre-selected terrain conditions. Even with complex suspension mechanisms, wheels can typically negotiate obstacles which are no more than about twice the wheel diameter. Furthermore, complex drive/transmission mechanisms make them more vulnerable. On the other hand, biologically inspired alternative mobility mechanisms and their control would offer adaptability to various terrain /ambient conditions. Bio-morphic explorers are a unique combination of direct-driven mobility designed using reconfigurable mobile units and their control by adaptive, fault tolerant biomorphic algorithms to autonomously match with the changing ambient/terrain conditions. With dedicated payload consisting of an imager or a few sensors, they act as our scouts, the front end to explore places where we do not have easy reach or the highest risk areas. Biomorphic controls will enable realization of application specific biomorphic explorers to implement the new scenarios for exploration.

Reconfigurable mobile units are inherently non-linear systems that are expected to be controlled most effectively by mechanisms that allow adaptation of control sequence to determine its parameters while acting on the target environment as required. The recent emergence of neuro-reflexive control, a powerful paradigm that offers real time adaptivity and learning ability with inherent fault tolerance, would make it possible to capture these attributes in an on-board, compact control hardware, not possible with conventional technology suite. Combining the reconfigurable, modular mobile units and bio-morphic controls would therefore offer for the first time a new direction in advanced mobility with new capabilities of adapting to terrain, enhanced spatial access owing to flexibility, scalability, and ease of multiplicity due to batch-process-amenable fabrication. A neural control would allow adaptation for a variety of environmental conditions by capturing a continuous mapping from sensor inputs to actuator trigger outputs for locomotion as well as actuator shape control.

The low cost for such biomorphic small dedicated explorers would result because of their highly modular designs, with interchangeable parts, manufactured (and stocked) in quantities. Given a mission/exploration scenario, one should be able to select appropriate modular blocks (just like Lego blocks), to build the desired explorer.

Finally, with all this optimism apparent, we must assess and advance the discipline of the biomorphic explorers with regard to (1) their *realistic promise* for scientific achievements, *as endorsed and recognized by the scientists*, and (2) the existing as well as projected capabilities of the relevant technologies, *as validated by the technology developers*. That is the intent and focus of this workshop.

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BIOMORPHIC EXPLORERS

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1st NASA/JPL WORKSHOP ON BIOMORPHIC EXPLORERS FOR FUTURE MISSION
August 19-20, 1998, Jet Propulsion Laboratory Auditorium: 180-101

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BIOMORPHIC EXPLORERS TEAM

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- BOB FRISBEE
- ZAREH GORJIAN
- BRETT KENNEDY
- JOHN MICHAEL MOROOKIAN
- KEN NEALSON
- ADRIAN STOICA
- ANIL THAKOOR
- SARITA THAKOOR

BIO-MORPHIC EXPLORERS

OUTLINE

- MOTIVATION
- BACKGROUND
- CONCEPT: KEY FEATURES
  - RECONFIGURABILITY
  - MODULARITY
- BIOMORPHIC CONTROLS
- ACTUATION TECHNOLOGIES
- EXPLORATION SCENARIOS
- WORKSHOP FOCUS

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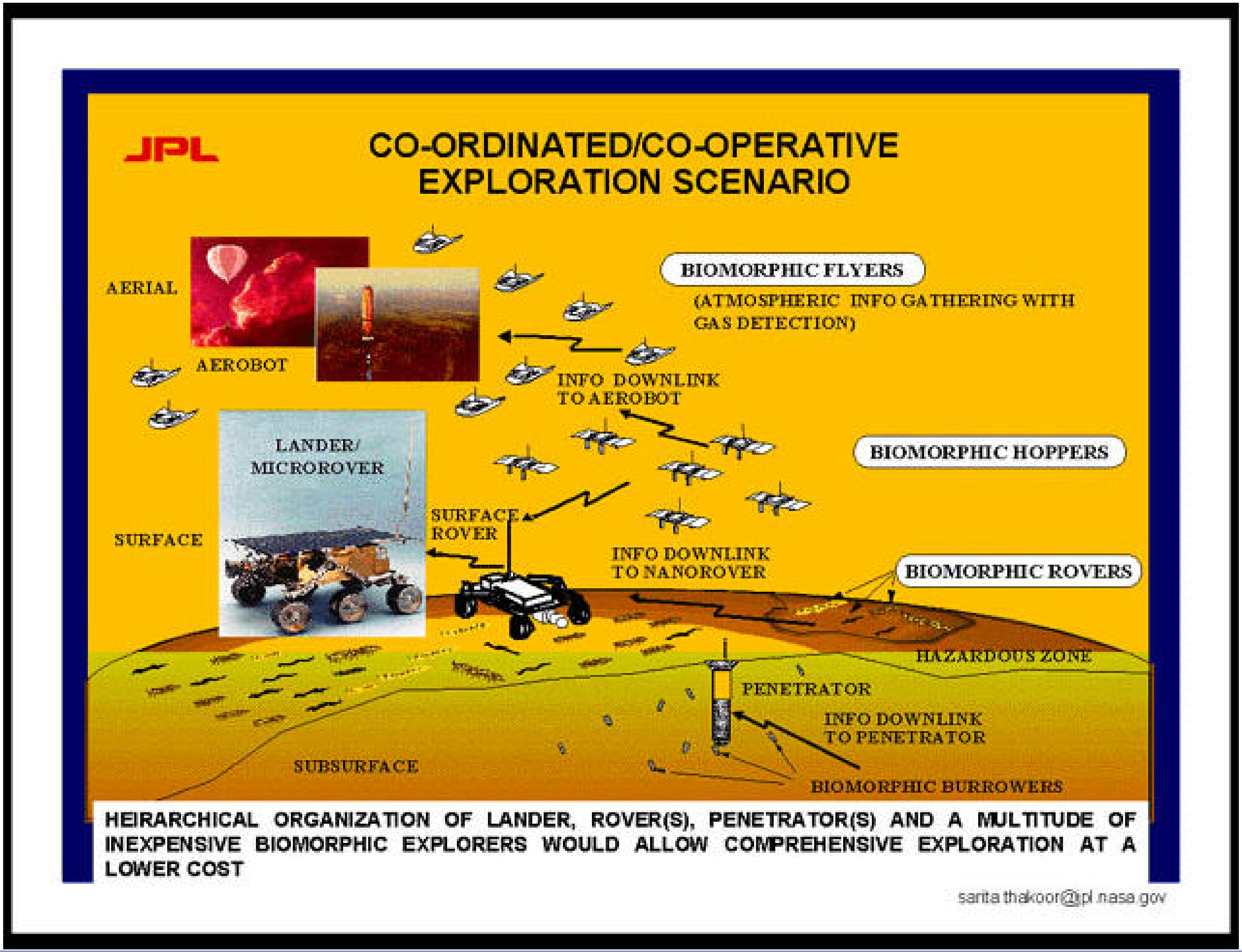
JPL
CO-ORDINATED/CO-OPERATIVE
EXPLORATION SCENARIO
AERIAL
AEROBOT
BIOMORPHIC FLYERS
(ATMOSPHERIC INFO GATHERING WITH
GAS DETECTION)
INFO DOWNLINK
TO AEROBOT
LANDER/
MICROROVER
BIOMORPHIC HOPPERS
SURFACE
SURFACE
ROVER
INFO DOWNLINK
TO NANOROVER
BIOMORPHIC ROVERS
HAZARDOUS ZONE
PENETRATOR
INFO DOWNLINK
TO PENETRATOR
SUBSURFACE
BIOMORPHIC BURROWERS
HEIRARCHICAL ORGANIZATION OF LANDER, ROVER(S), PENETRATOR(S) AND A MULTITUDE OF INEXPENSIVE BIOMORPHIC EXPLORERS WOULD ALLOW COMPREHENSIVE EXPLORATION AT A LOWER COST
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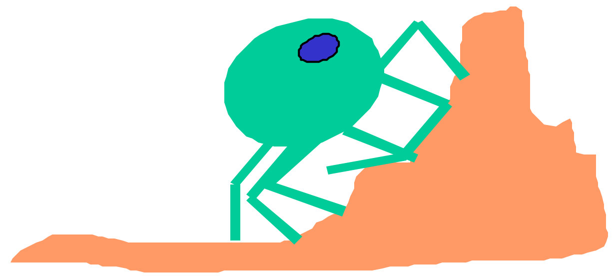
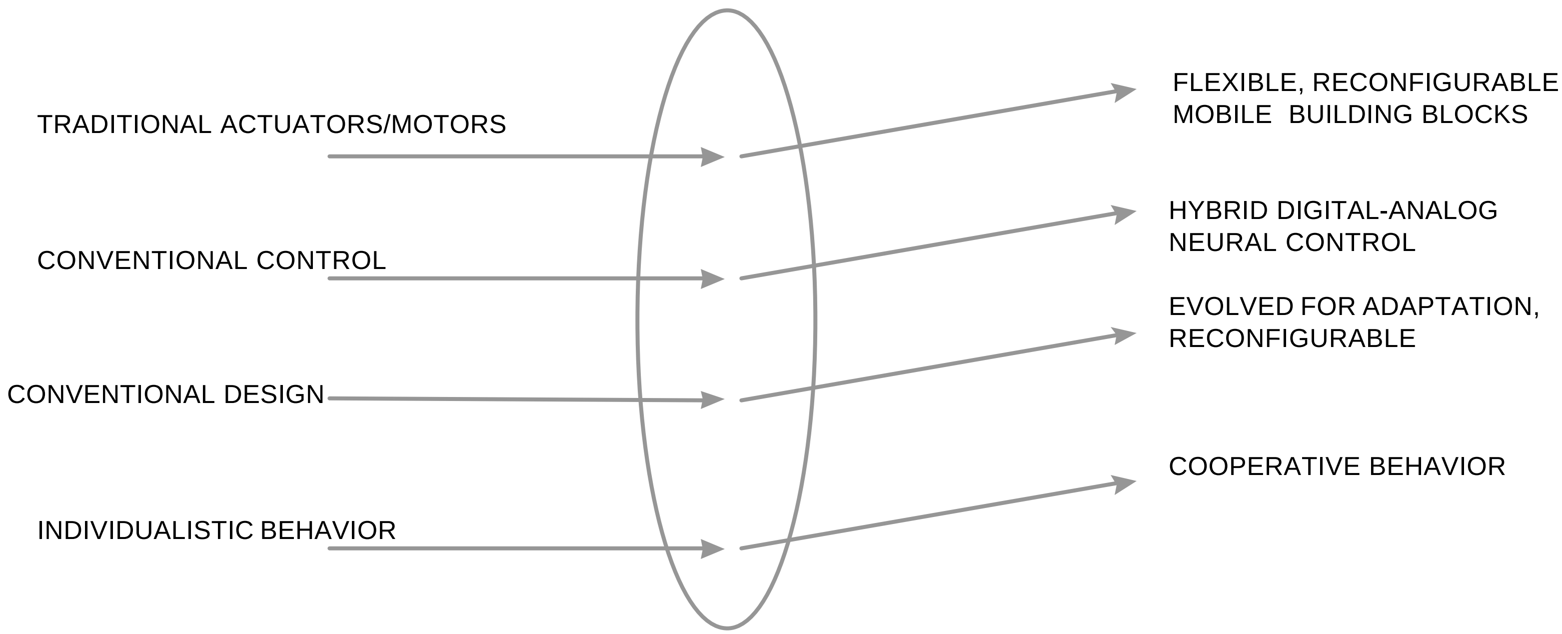
MOTIVATION: PARADIGM SHIFT FOR ENHANCED SCIENCE RETURN

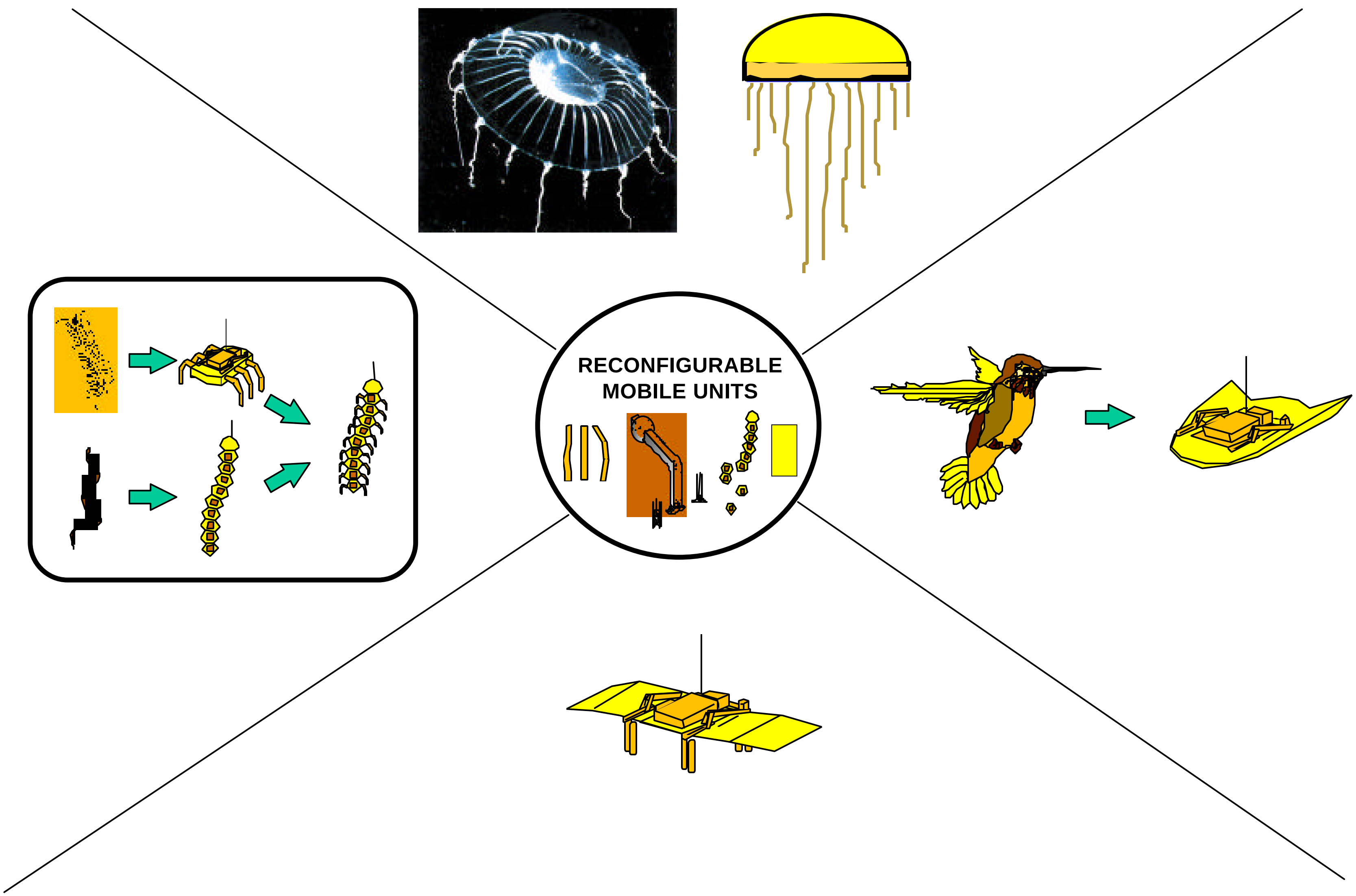
CURRENT ROVERS

BIOMORPHIC EXPLORERS





ADVANCED MOBILITY FOR BIO-MORPHIC EXPLORERS



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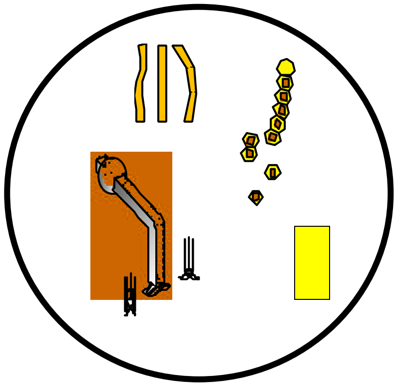
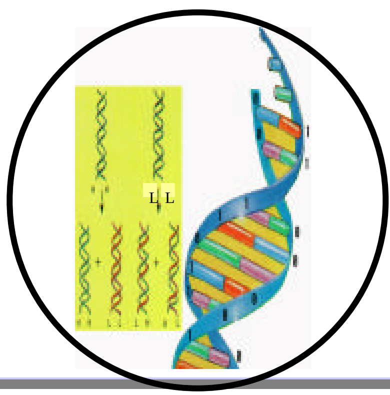
CONCEPT: BIO-MORPHIC EXPLORERS

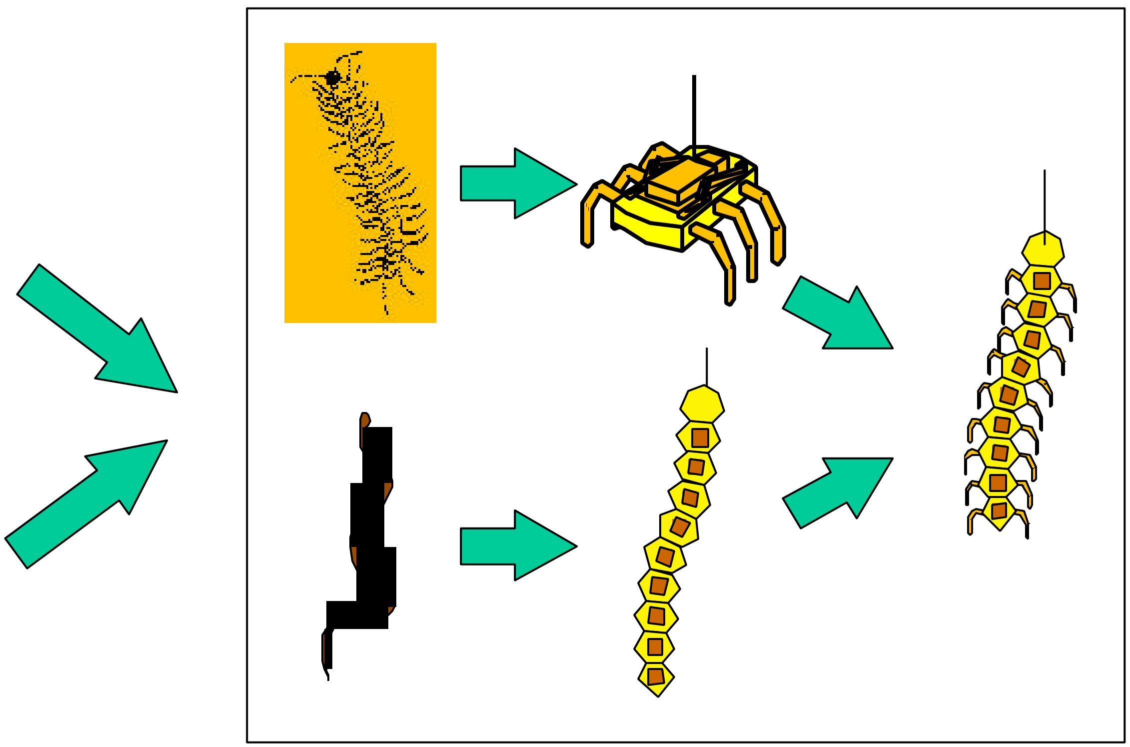
- **BIO-MORPHIC EXPLORERS: A UNIQUE COMBINATION OF <u>DIRECT-DRIVEN</u> MOBILITY DESIGNED USING RECONFIGURABLE MOBILE UNITS and THEIR CONTROL BY ADAPTIVE, FAULT TOLERANT BIOMORPHIC ALGORITHMS TO AUTONOMOUSLY MATCH WITH THE CHANGING AMBIENT/TERRAIN CONDITIONS.**

RECONFIGURABLE MOBILE UNITS



BIOMORPHIC CONTROL





KEY FEATURES OF BIOMORPHIC EXPLORERS

- MODULAR, BUILDING BLOCK DESIGN
- RECONFIGURABILITY
- MULTITERRAIN CAPABILITY
- LOW COST BEACONS/SCOUTS
- LEARNING CAPABILITY
- ADAPTABILITY
- CO-OPERATIVE BEHAVIOR

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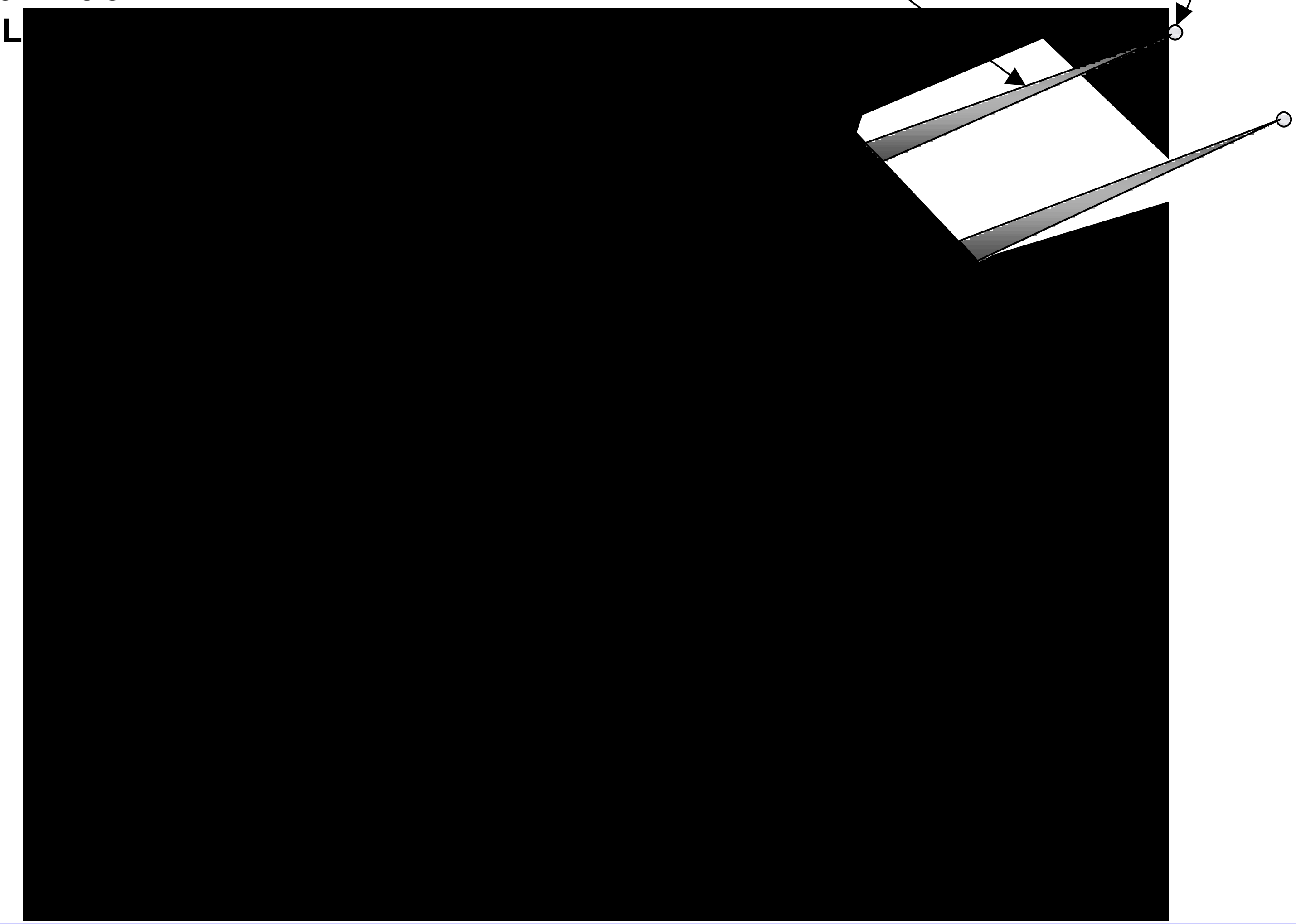
MULTITERRAIN RECONFIGURABLE LEGGED EXPLORER



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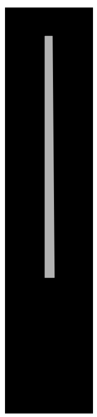
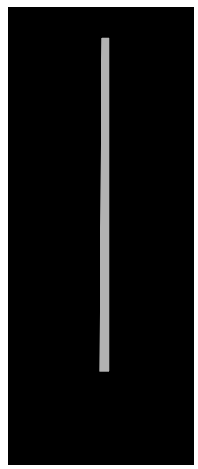
RECONFIGURABLE FOOT/LEG OF BIOMORPHIC EXPLORER



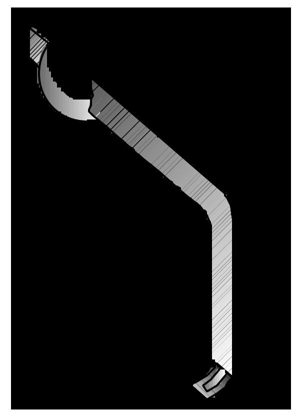
NARROW FOOTPRINT

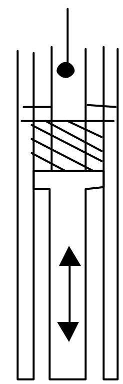
‘a’



WIDE FOOTPRINT

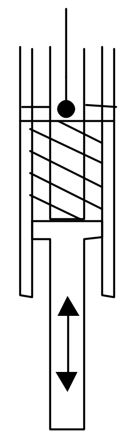
‘b’





SHORT LEG

‘c’



LONG LEG

‘d’

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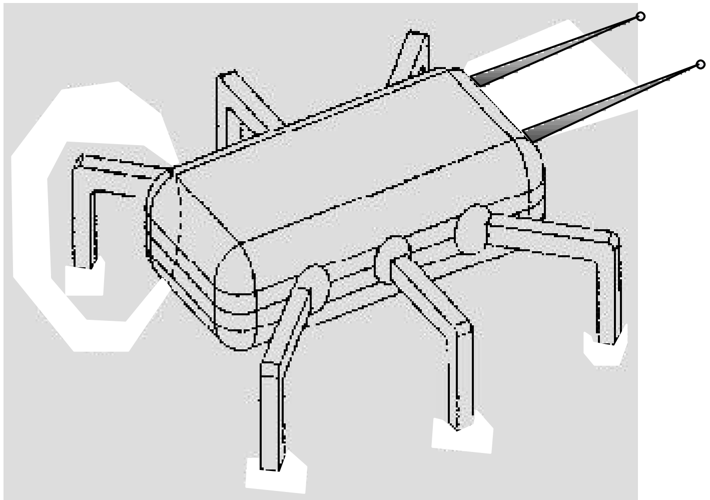
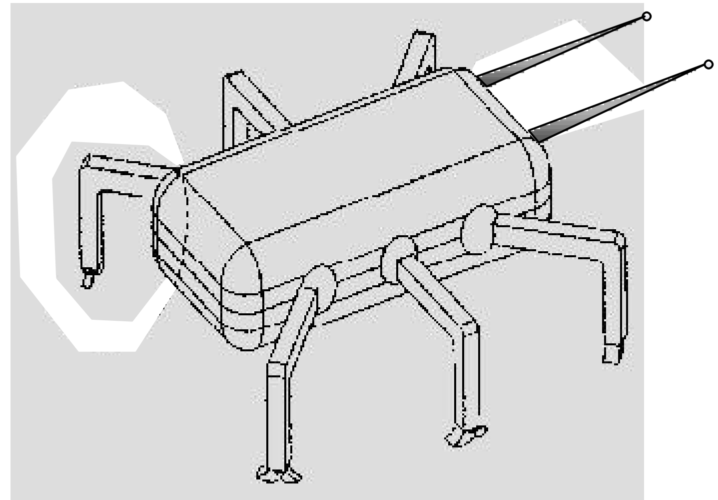
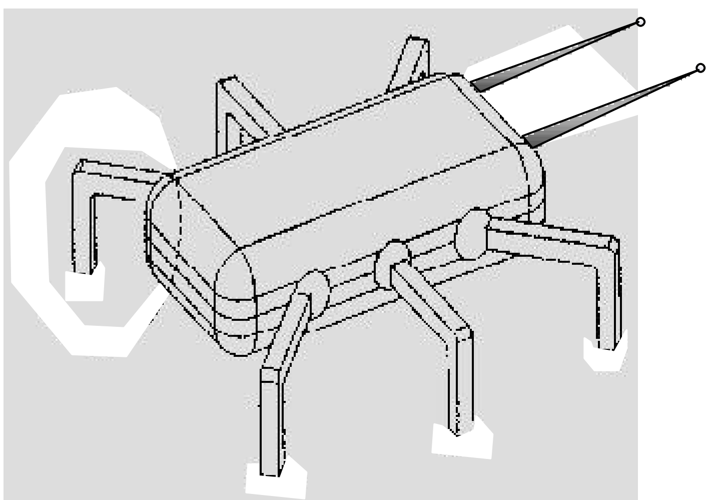
MULTITERRAIN RECONFIGURABLE LEGGED EXPLORER



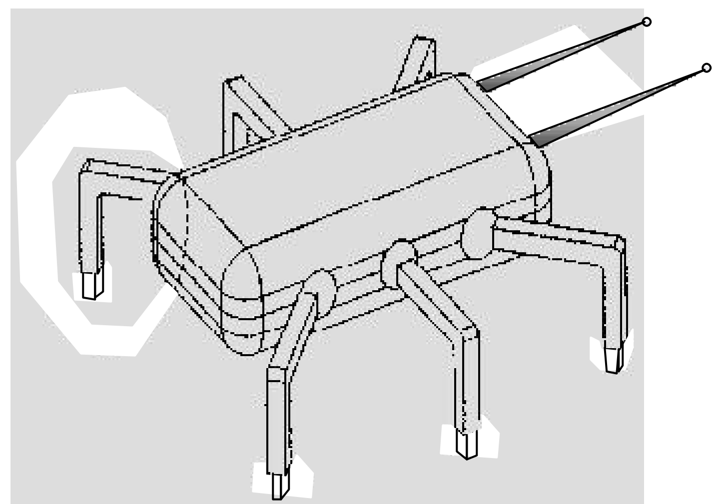
NARROW FOOTPRINT



WIDE FOOTPRINT



SHORT LEG



LONG LEG

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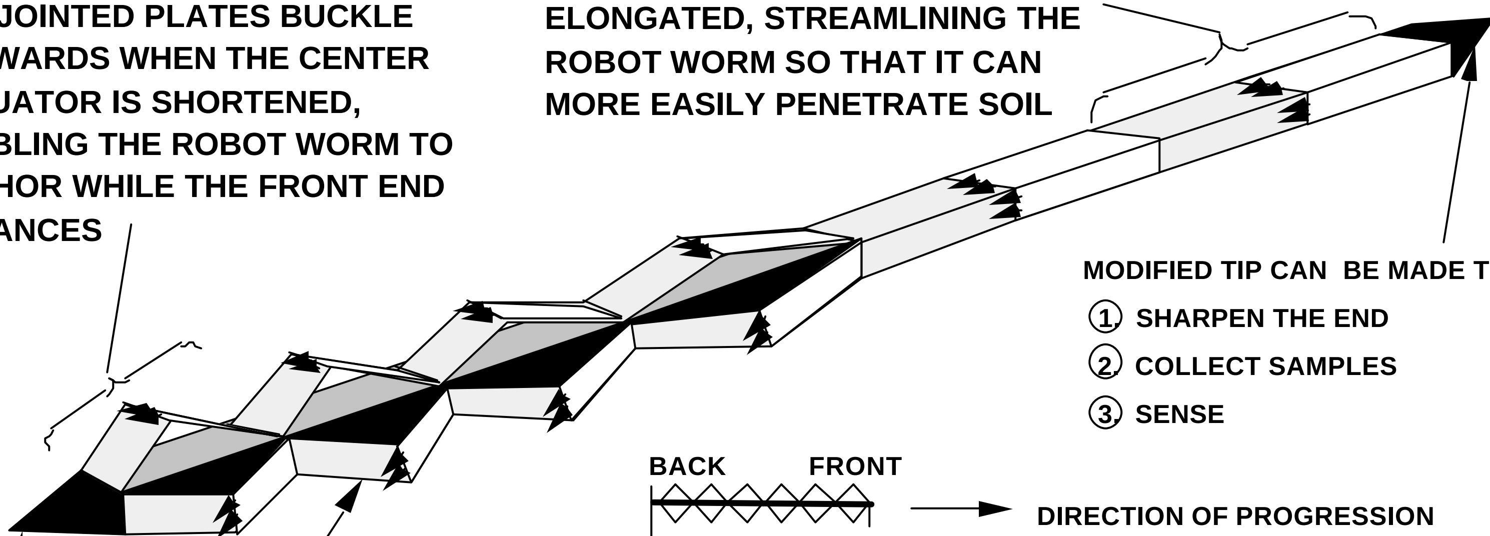
EARTHWORM LIKE BURROWING ROBOT

THE JOINTED PLATES BUCKLE OUTWARDS WHEN THE CENTER ACTUATOR IS SHORTENED, ENABLING THE ROBOT WORM TO ANCHOR WHILE THE FRONT END ADVANCES

THE JOINTED PLATES LAY FLAT WHEN THE CENTER ACTUATOR IS ELONGATED, STREAMLINING THE ROBOT WORM SO THAT IT CAN MORE EASILY PENETRATE SOIL

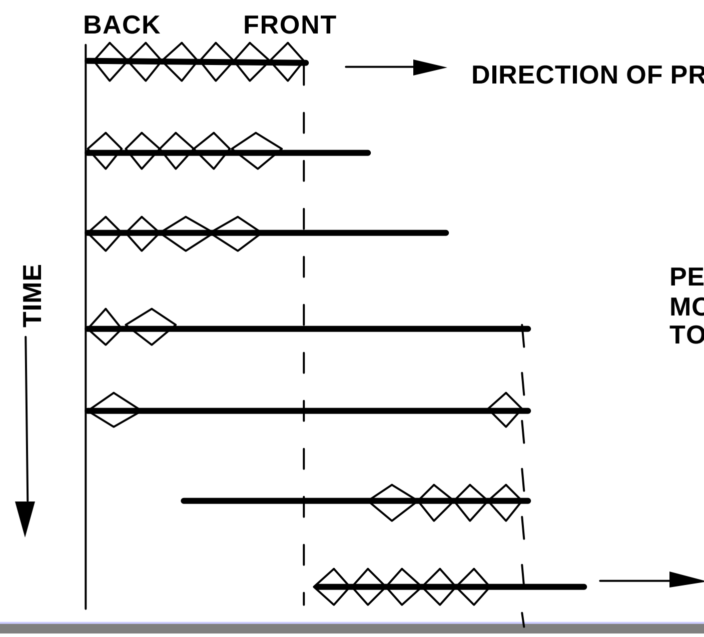


MODIFIED TIP CAN BE MADE TO:

1. SHARPEN THE END
2. COLLECT SAMPLES
3. SENSE

LITTLE SPIKES ON THE PLATES PROVIDE FURTHER TRACTION ONLY WHEN THE PLATES ARE IN THE BUCKLED POSITION

MOTION COULD BE MADE BI-DIRECTIONAL BY CHANGING SEQUENCE OF SEGMENT SHORTENING AND ELONGATION BY ACTUATORS



PERISTALSIS-LIKE MOTION SIMILAR TO EARTHWORMS

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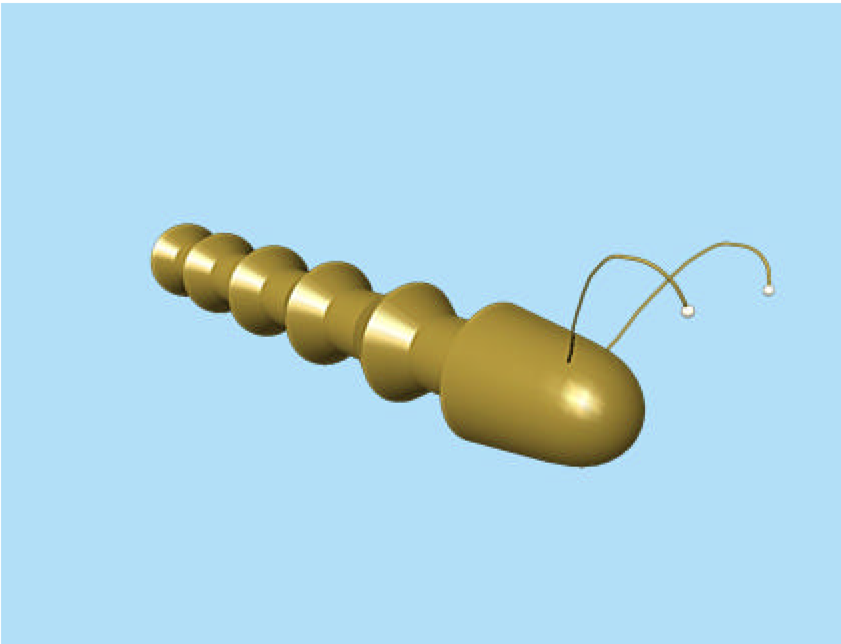
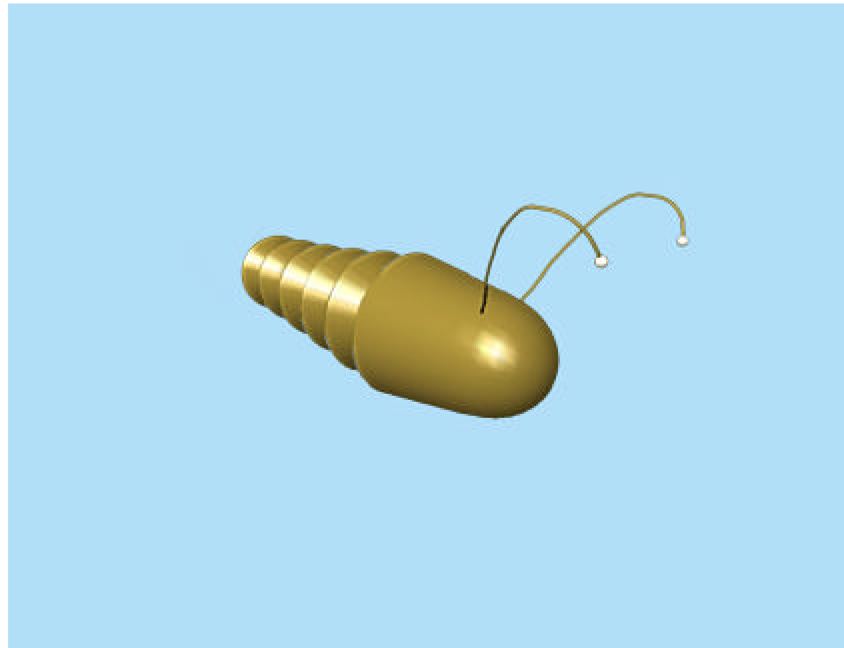
WORM ROBOT FOR IN-SITU EXPLORATION



EXTENDED CONFIGURATION

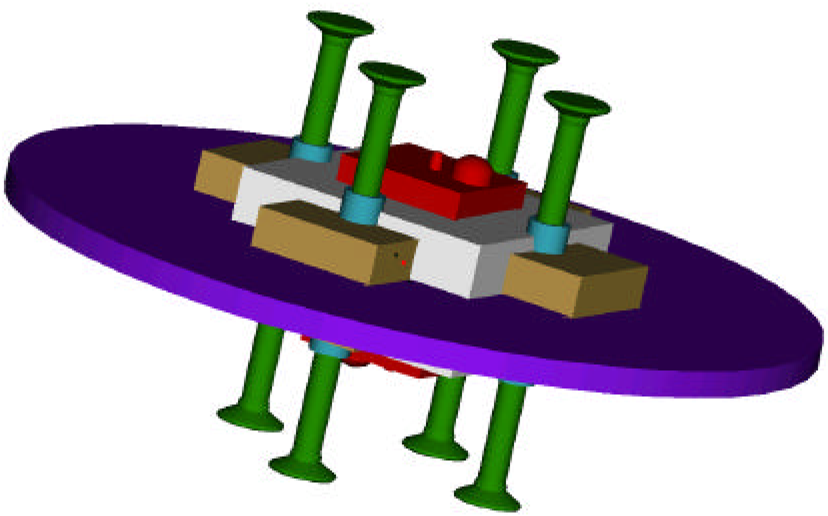


CONTRACTED CONFIGURATION

*Z. Gorjian and S. Thakoor, "Biomorphic Explorers Animation Video", 1st NASA/JPL WORKSHOP ON BIOMORPHIC EXPLORERS FOR FUTURE MISSIONS, August 19-20, 1998; Jet Propulsion Laboratory, Pasadena, CA

Conceptual design

- Four pistons provide thrust and direction
- Closed H and O_2 fuel system
- Possibly symmetric top/bottom
- Single experiment package



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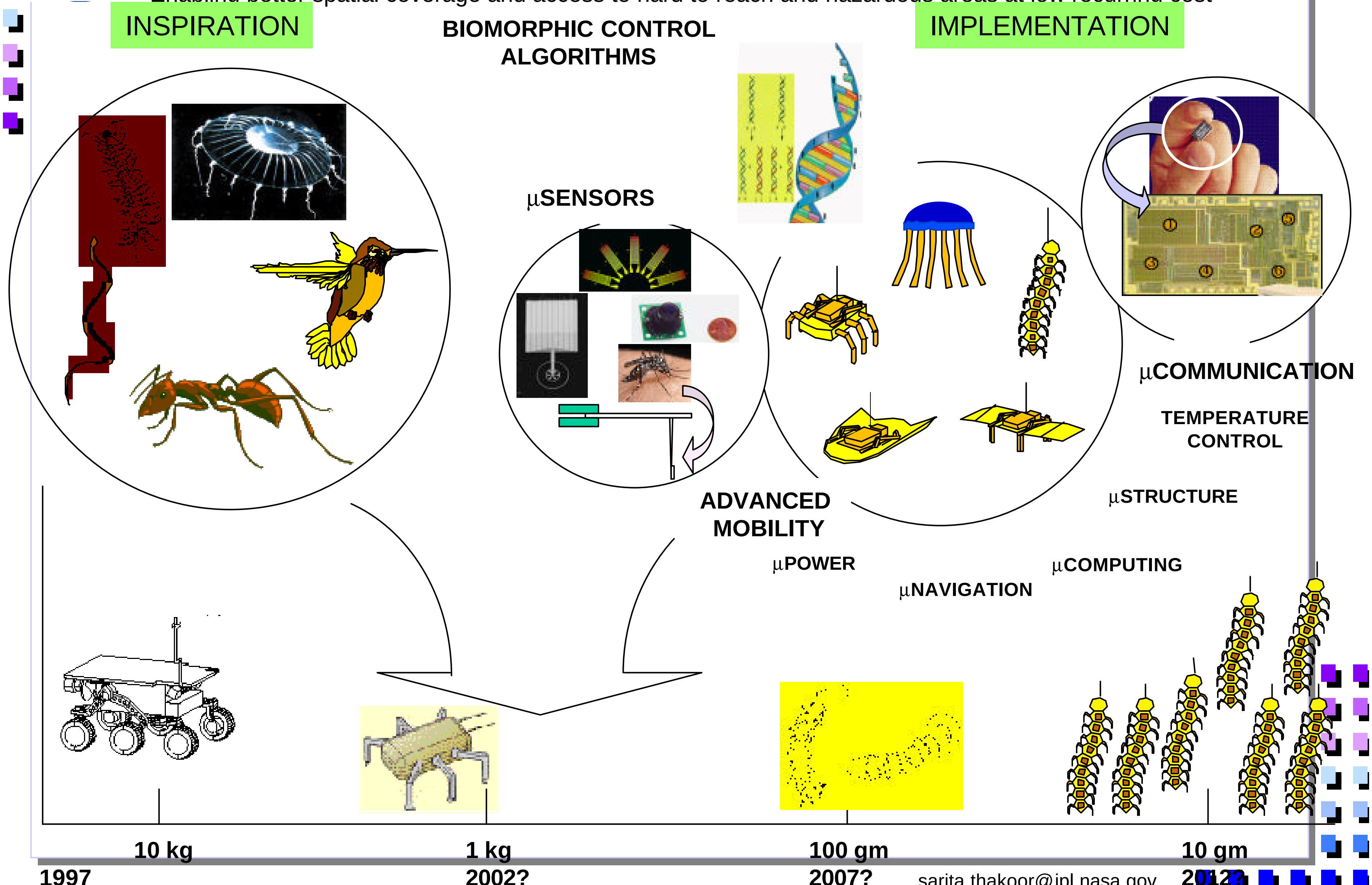
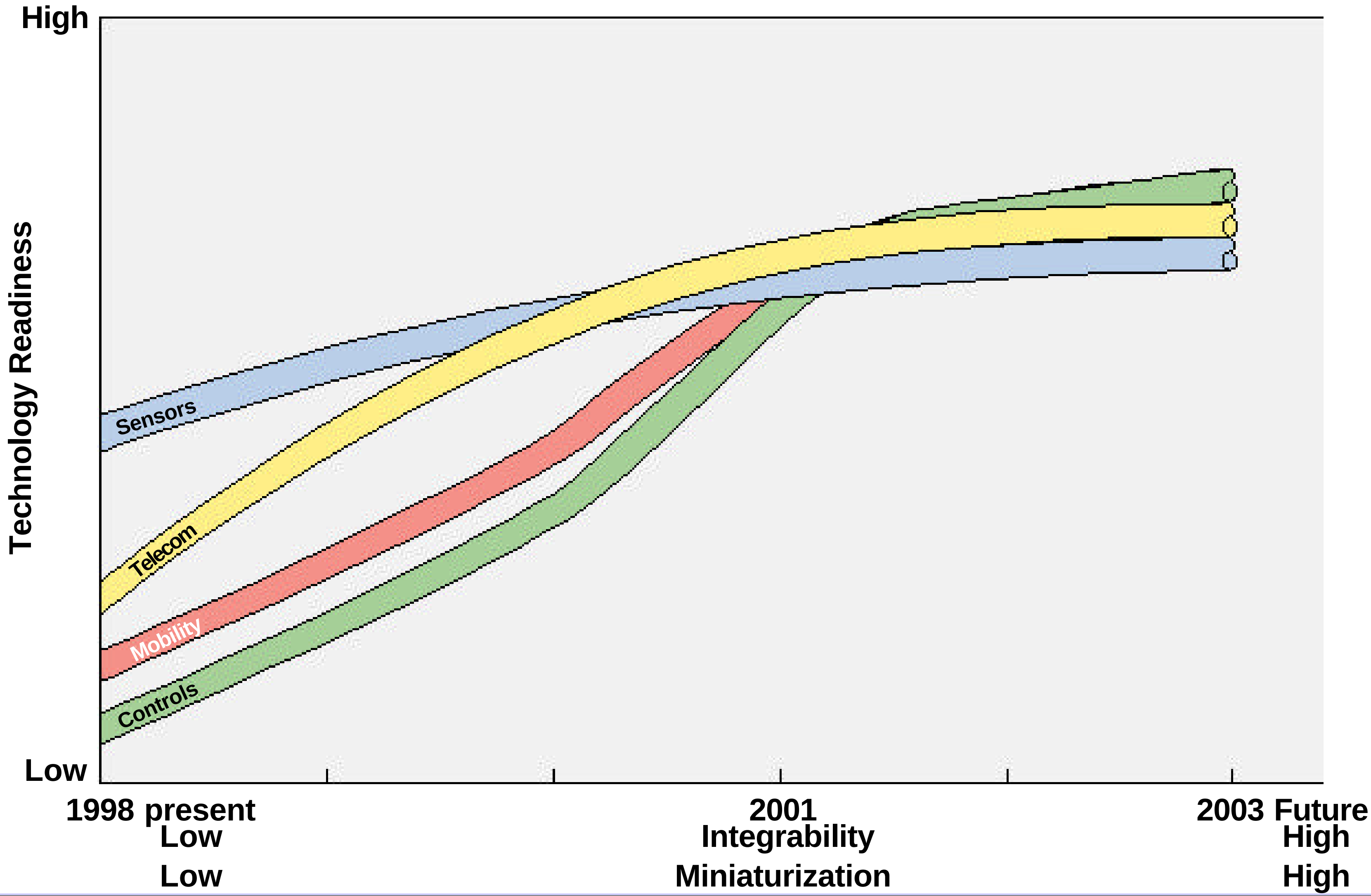
Biomorphic Explorers

Enabling better spatial coverage and access to hard to reach and hazardous areas at low recurring cost





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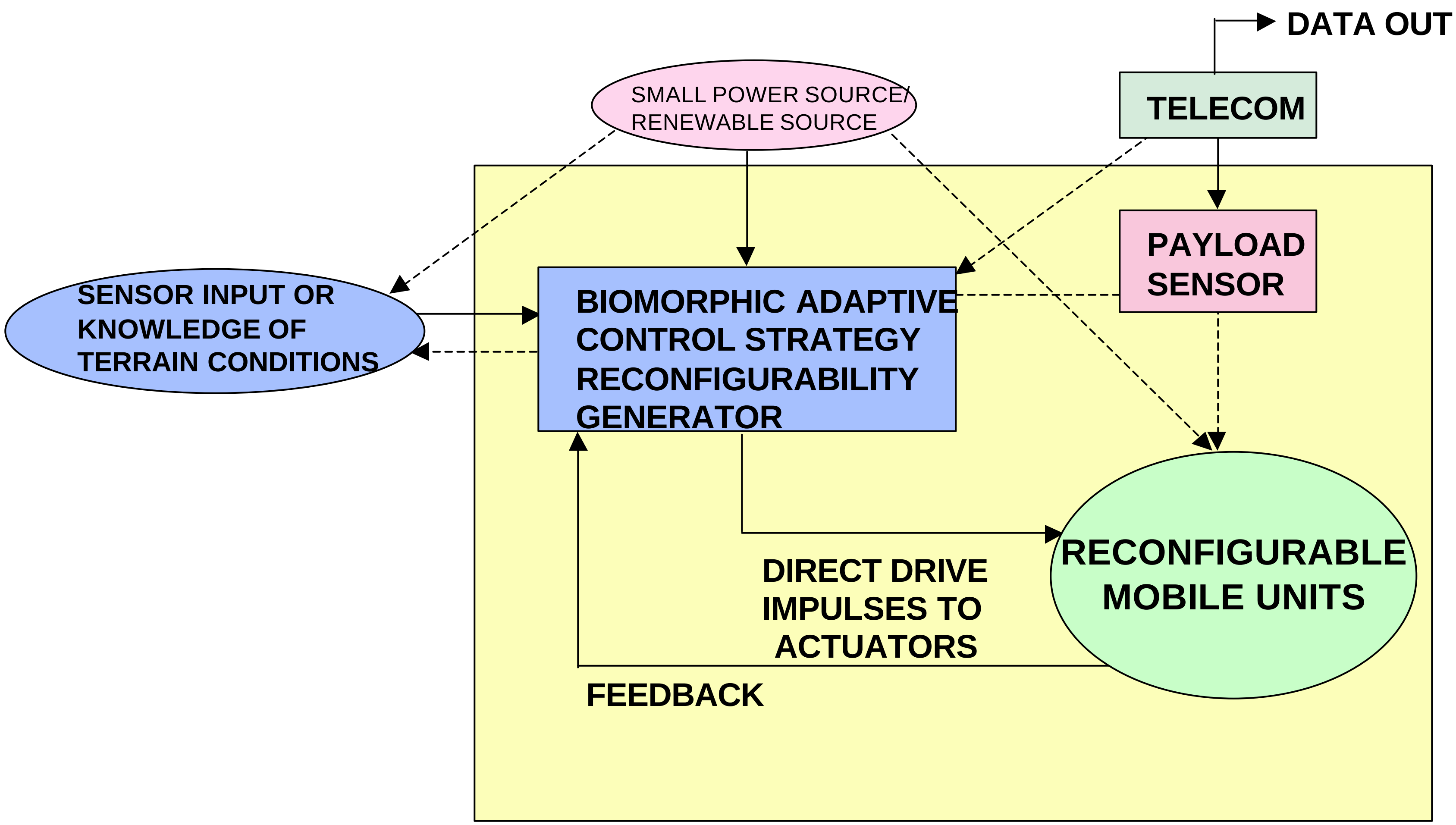
Distributed Control Operational Schematic



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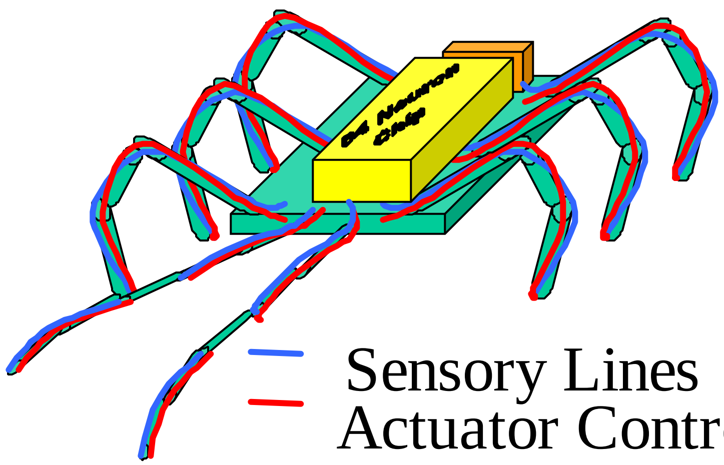
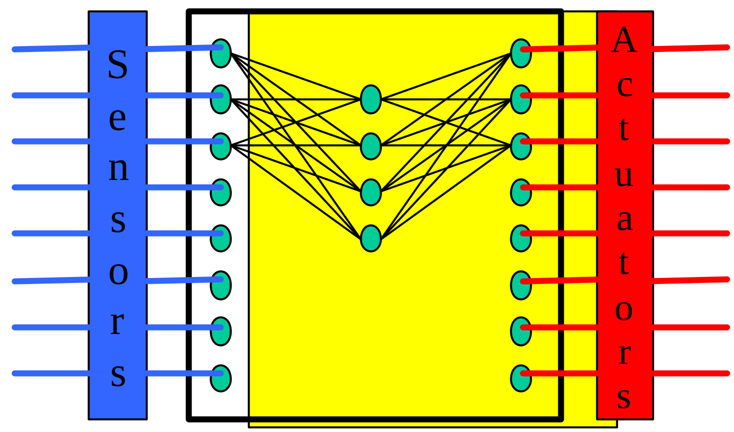
Neurally-controlled Biomorphic Explorer

Neural connections mapped on 64 Neural Network (NN) Chip



Sensory Lines
Actuator Controls



JPL' s64 NN chip Characteristics:

- Low Weight (5g)
- Small Size (1cm x 1cm)
- Low Power (12mW)
- High Speed (~250nsec)
- Programmable Neural Network Architecture

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ADVANCED MOBILITY
ACTUATION TECHNOLOGIES COMPARISON

			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	PVDF and PVDF copolymers	Polymides PMMA Polyurethanes	MAGNETO-STRICTIVE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL: MARTENSITIC ® AUSTENITIC PHASE CHANGE	PIEZOELECTRIC, PHASE TRANSITION	ELECTRO-STRICTIVE	MAGNETIC FIELD INDUCED BY COIL
STRAIN	10^{-4} TO $0.3X10^{-2}$	10^{-5} TO 10^{-1}	10^{-6} TO 10^{-1}	10^{-9} TO 10^{-1}	10^{-5} TO 10^{-2}
DISPLACEMENT	LOW TO HIGH	MEDIUM TO HIGH	LOW TO HIGH	LOW TO MEDIUM	MEDIUM
FORCE (in Newtons)	HIGH ~ 100-1000	MEDIUM ~ 1-10	SMALL	SMALL	HIGH
HYSTERISIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	–196°C ® 300°C WIDE	–196°C ® 100°C WIDE	–50°C ® 150°C MEDIUM	–10°C ® 80°C LIMITED	-273°C ® 100°C WIDE
RESPONSE SPEED	µsec-msec	seconds	µsec-msec	µsec-msec	µsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW to MEDIUM	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	YES	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR–POOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

THE SURVEY SUGGESTS LEADING CANDIDATES AND THEIR HIGHLIGHTED ATTRIBUTES

Innovative combinations of flexible actuators are conceptualized to address specific applications

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FLEXIBLE ACTUATORS: INNOVATION OPTIONS

MATERIAL INNOVATION	FABRICATION CHALLENGE	PAY-OFF	FEATURES ENHANCED
I Shape memory alloy wire, Piezoceramics	LOW	MEDIUM	HIGH FORCE, MEDIUM DEFLECTION WIDE TEMP RANGE OPERATION MEDIUM SPEED, ELECTRICALLY OPERATED
II Piezoceramics thin film/high temp. polymers	MEDIUM	MEDIUM	MEDIUM FORCE, HIGH DEFLECTION SCALEABLE, MEMS WIDE TEMP RANGE OPERATION MEDIUM SPEED, ELECTRICALLY OPERATED
III Optical Piezoceramics / high temp. polymers, polymeric actuators	HIGH	HIGH	HIGH FORCE& DEFLECTION COMBINATION, SCALEABLE, MEMS WIDE TEMP RANGE OPERATION HIGH SPEED, ELECTRICALLY & OPTICALLY OPERABLE

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EARTH - MARS COMPARISON

	EARTH	MARS
GRAVITY (M/sec^2)	9.8	3.7
ATMOSPHEREIC PRESSURE (DYNES/cm^2)	1×10^6	5.6×10^3
INSOLATION (W/M^2)	1340	1367
AVERAGE SURFACE TEMPERATURE (K)	~ 300	~ 210

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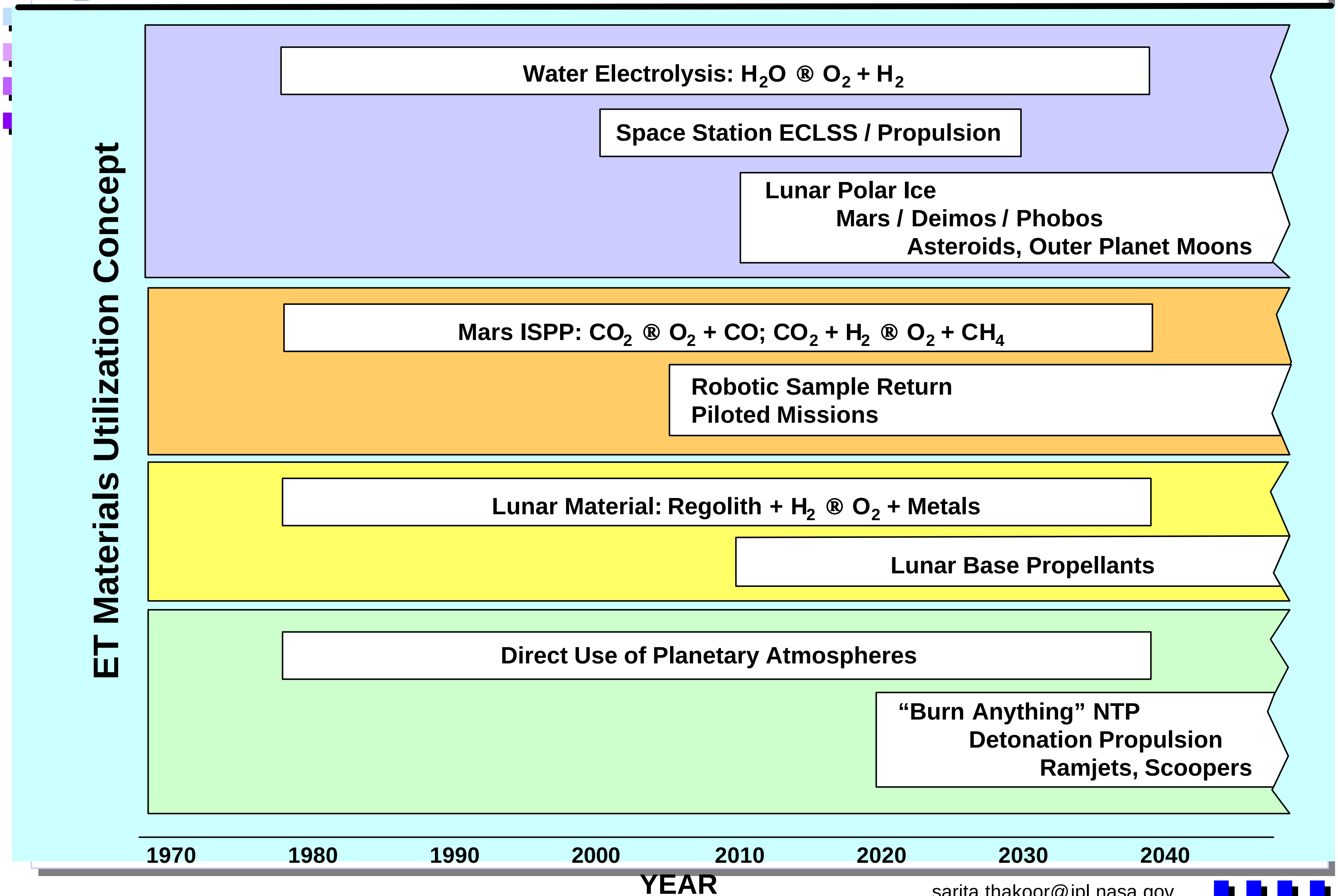
EXTRATERRESTRIAL RESOURCE UTILIZATION (ETRU) APPLICATIONS



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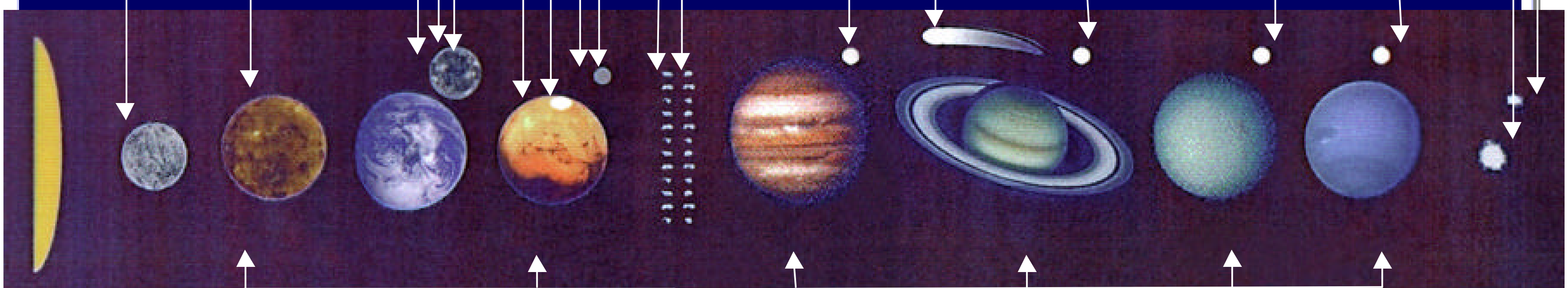
ETRU FEEDSTOCKS / PROCESSES/OUTPUTS / LOCATIONS

Feedstock	Regolith (Soil)	Surface Regolith	Water (Water-Ice)
Process	Chemical Reduction of Regolith	Bake Regolith	Water Electrolysis
Output	O_2, Metals (“Stag”)	Trace Gases (H_2, N_2, He_3, etc.)	H_2, O_2



Feedstock	CO_2 (Atmosphere)	CO_2, H_2, (H_2O) (HT, from Earth?)	Outer-Planet Atmosphere
Process	Zirconia “Electrolysis”	Sabatier + Water Electrolysis	“Scoop” from Atmosphere
Output	O_2, CO	O_2, CH_4	H_2, CH_4, He_3

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SCENARIO 1
MARS

- **WORM ROBOTS SCATTERED AROUND MARS TERRAIN**
  - **TO CRAWL INTO CRACKS**
  - **TO BURROW IN SOFT LOOSE SOIL**
  - **TO GO UNDER ROCKS**
- **IN-SITU SENSING / SAMPLE RETRIEVAL FROM HARD-TO-REACH PLACES**

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SCENARIO 2
MARS : VALLES MARINERIS

- **GLIDERS, DISC EXPLORERS DEPLOYED FROM ORBITER OR LARGER AERIAL CRAFT TO FALL IN CONTROLLED MANNER INTO THE MARS CANYONS**
  - **TO COLLECT STRATIGRAPHY DATA**
  - **IMAGING OF THE CANYON WALLS**
    - **SEDIMENTARY LAYERS OF ROCKS**
    - **VOLCANIC LAYER DEPOSITS**
  - **ATMOSPHERIC, METEOROLOGICAL DATA**

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SCENARIO 3

- **HOPPERS JUMPING FROM LEVEL TO LEVEL, GROUND UP**
  - **TO IMAGE AND EXPLORE THE CANYONS FROM BOTTOM UP, PARTICULARLY TO LOOK AT THE LAYER SEDIMENTS AT THE BOTTOM OF THE CANYONS**

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SCENARIO 4

LAKE VOSTOK IN THE ANTARCTIC

500,000 to 1,000,000 years old

http://www.usatoday.com/life/science/space/lss002.htm

- **A BODY OF WATER THE SIZE OF LAKE ONTARIO LIES BENEATH 4 MILES OF ICE (SUBSURFACE OCEAN IN ICELAND)**
  - **TO STUDY BACTERIA AND OTHER MICRO-ORGANISMS**
  - **NURTURED (THRIVING ?) IN THE DEEP OCEANS UNDER THE THICK ICE LAYERS**
- **EUROPA : ONE OF THE JUPITER'S MOONS APPEARS TO HAVE AN OCEAN BENEATH ITS ICY CRUST. OCEAN MIGHT HARBOR LIFE THAT NEEDS TO BE EXPLORED..**
  - **WILL ALLOW EXHAUSTIVE SEARCH RATHER THAN POINT SAMPLES TO LOOK FOR LIFE**

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Pay-Off

Inspired by the numerous examples of successful "explorers" in biology (real proof-of-existence), small, autonomous, biomorphic explorers promise to enhance planetary/ space exploration through:

- Enhanced Science With the Use of Many Small Explorers
- Better Spatial Coverage in a Short Duration
- Access to Hard-to-Reach Areas
- Dedicated Microsensing
- Low Recurring Cost

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BIOMORPHIC EXPLORERS
DUAL USE TECHNOLOGY APPLICATIONS

….WHICH WOULD BE ENHANCED/ENABLED BY SUCH EXPLORERS…..

NASA

- **SEARCH FOR EVIDENCE OF LIFE**
  - **WIDE AREA SEARCH WITH INEXPENSIVE EXPLORERS EXECUTING DEDICATED SENSING FUNCTIONS**

  ….Individual gases, chemical reactions, elements, specific amino acids, etc

- **GEOLOGICAL DATA GATHERING:**
  - **DISTRIBUTED TEMPERATURE SENSING**
  - **SEISMIC ACTIVITY MONITORING**

  ….Multitude of explorers working in a cascade or daisy chain fashion co-operatively to fulfill task

DOD

- **OTHER (TERRESTRIAL) APPLICATIONS:**
  - **LAW ENFORCEMENT, SECURITY AND SURVEILLENCE**
  - **SEARCH AND RESCUE OPERATIONS**
  - **CHEMICAL AND BIOLOGICAL WARFARE AGENT MONITORING**
  - **URBAN WARFARE**

NIH

- **TARGETED MICROEXPLORERS INJECTED IN HUMAN PATIENT BODY**
  - **TO CLEAR UP CANCER CELLS/TISSUE**
  - **DIAGNOSIS OF INTERNAL TRAUMA**

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BIO-MORPHIC EXPLORERS

WORKSHOP FOCUS

ASSESS THE DISCIPLINE OF THE BIOMORPHIC EXPLORERS WITH RESPECT TO:

(1) THEIR *REALISTIC PROMISE* FOR SCIENTIFIC ACHIEVEMENTS, *AS RECOGNIZED AND ENDORSED BY THE SCIENTISTS*, AND

(2) THE EXISTING AS WELL AS PROJECTED CAPABILITIES OF THE RELEVANT TECHNOLOGIES, *AS VALIDATED BY THE TECHNOLOGY DEVELOPERS*.

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